Functionally Designed Ultra-lightweight Carbon Fiber Reinforced Thermoplastic Composites Door Assembly

Project ID: mat118

DOE Vehicle Technologies Office Annual Merit Review, Online, June 1 - 4, 2020

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Overview

Timeline

- Start: December 1, 2015
- End: November 30, 2020
- 80 % Complete

Budget

- **Total project funding**
  - $2,249,994 (DOE)
  - $3,117,759 (Cost-share)
- **Funding for Budget Period 1 (12/1/2015 - 1/31/2017)**
  - $642,819 (DOE)
  - $871,357 (Actual Cost-share)
- **Funding for Budget Period 2 (2/1/2017 - 01/31/2018)**
  - $624,023 (DOE)
  - $674,889(Actual Cost-share)
- **Funding for Budget Period 3 (2/1/2018 - 01/31/2019)**
  - $643,239 (DOE)
  - $846,747(Actual Cost-share)
- **Funding for Budget Period 4 (2/1/2019 - 11/30/2020)**
  - $ 339,913 (DOE)
  - $ 773,906 (Actual Cost-share)

Barriers

- **Cost/Performance**
  - High cost of CFRP is the greatest barrier to the market viability of advanced composites for automotive lightweight applications.
  - Meeting CFRP-Thermoplastics performance to satisfy/exceed fit, function, crash and NVH at desired cost.
- **Predictive tools**
  - Integration of predictive models between systems (design/geometry/process/analysis) and at all length scales.

2017 U.S DRIVE MTT Roadmap report, section 5.1

Core-Partners

- Clemson University
- University of Delaware
- Honda North America

Relevance: Project Objectives

1. **Achieve a 42.5% weight reduction (addresses goals in the DOE-VT MYPP)**
   - Base weight = **31.8 kg**
   - Target Weight = **18.28 kg**

2. **Zero compromise on performance targets**
   - Similar crash performance
   - Similar durability and everyday use/misuse performance
   - Similar NVH performance

3. **Maximum cost induced is 5$ per pound saved**
   - Allowable increase = **$ 150.1 per door**

4. **Scalability**
   - Annual production of **20,000 vehicles**

5. **Recyclability**
   - European standards require at least **95 %** recyclability
   - Project goal is 100% recyclable (self imposed)

Milestones

- ✓ Establish design criteria (FY 2015-2016)
- ✓ Develop a detailed target catalogue (FY 2015-2016)
- ✓ Create a test and evaluation plan (FY 2015-2012)
- ✓ Benchmark the current door (FY 2015-2016)
- ✓ Test and catalogue commercially available materials (FY 2015-2016)
- ✓ Design and develop three functional door concepts that can meet project targets. (FY 2015-2016)
- ✓ Design optimization for non-linear load cases (Crash requirements) (FY 2017-2018)
- ✓ Down select design concept for concept detailing (FY 2016-2017)
- ✓ Design optimization for linear load cases (Use and misuse) (FY 2016-2018)
- ✓ Design optimization for non-linear load cases (Crash requirements) (FY 2018-2019)
- ✓ Fit and function testing with thermoset prototype door(FY 2018-2019)
- ✓ Sub-component testing (FY 2019 Q3)
- ✓ Final cost estimation (FY 2019 Q4)
- ✓ Design release for tooling (FY 2020 Q1)

COVID-19

- Delayed - Tooling design (FY 2020 Q2)
- Not Started - Tool manufacturing (FY 2020 Q2-Q3)
- Not Started - Prototype manufacturing (FY 2020 Q3-Q4)
- Not Started - Final door crash testing (FY 2020 Q4)

Approach

Phase 1	Phase 2	Phase 3	Phase 4

Phase 1

Benchmarking & Target Definition

Frame **60% Reduction**

Window **20% Reduction**

Electronic **0% Reduction**

Trim **30% Reduction Or elimination**

Baseline Door (This project) **31.1 kg**

Material data generation

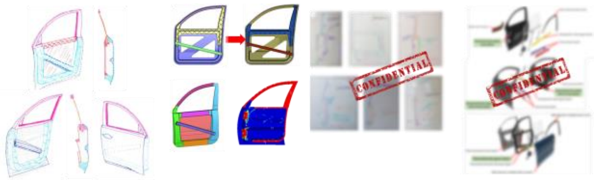
$$\begin{Bmatrix} f_1 \\ V_1 \\ M_1 \\ f_2 \\ V_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 & 0 & -\frac{AE}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{AE}{L} & 0 & 0 & \frac{AE}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}$$

Mat 8 (Static Simulations)
MAT 54 (Dynamic Simulations)

Unidirectional PA 6 CF 50 wt %
Woven PA 6 CF 50 wt %

Phase 2

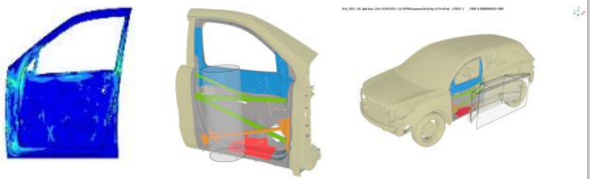
Concept development



Extensive concept development
Systems level approach
Aggressive parts consolidation

Concepts developed **6 → 3 → 1**
Baseline Structural Parts **17**
ULCW Door Structural Parts **8**

FEA simulations



Door optimized for and passes
8 Static Cases
(Door sag, Sash rigidity …)
3 Dynamic cases
OEM requirement > FMVSS 214 targets

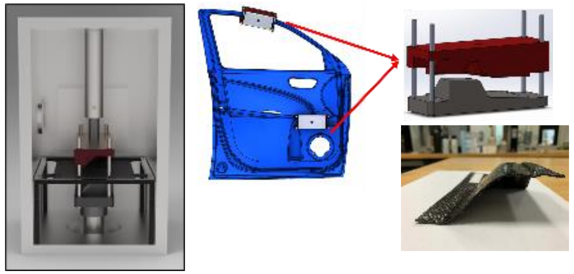
Phase 3

Subcomponent testing

Calibrating and Validating MAT 54 Cards in Dynamic environment

Cost Analysis **Parametric cost model**
Fit and Finish **Low cost prototype fabricated (Passed)**

Thermoforming trials



Developing a manufacturing to response pathway

Phase 4

Tooling + Prototyping

Leveraging experience of suppliers like Proper Tooling + Corning + Lanxess

Currently in last phase of project

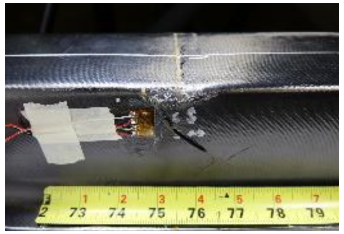
Testing

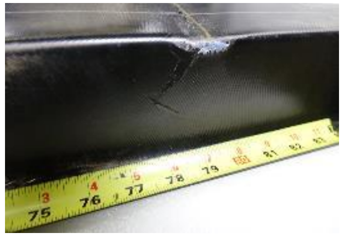
SOP's for static and dynamic tests to be finalized by OEM

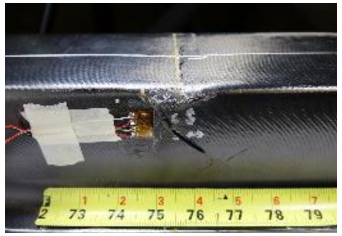
Progress: Subcomponent Testing

Impact testing on composite hat section

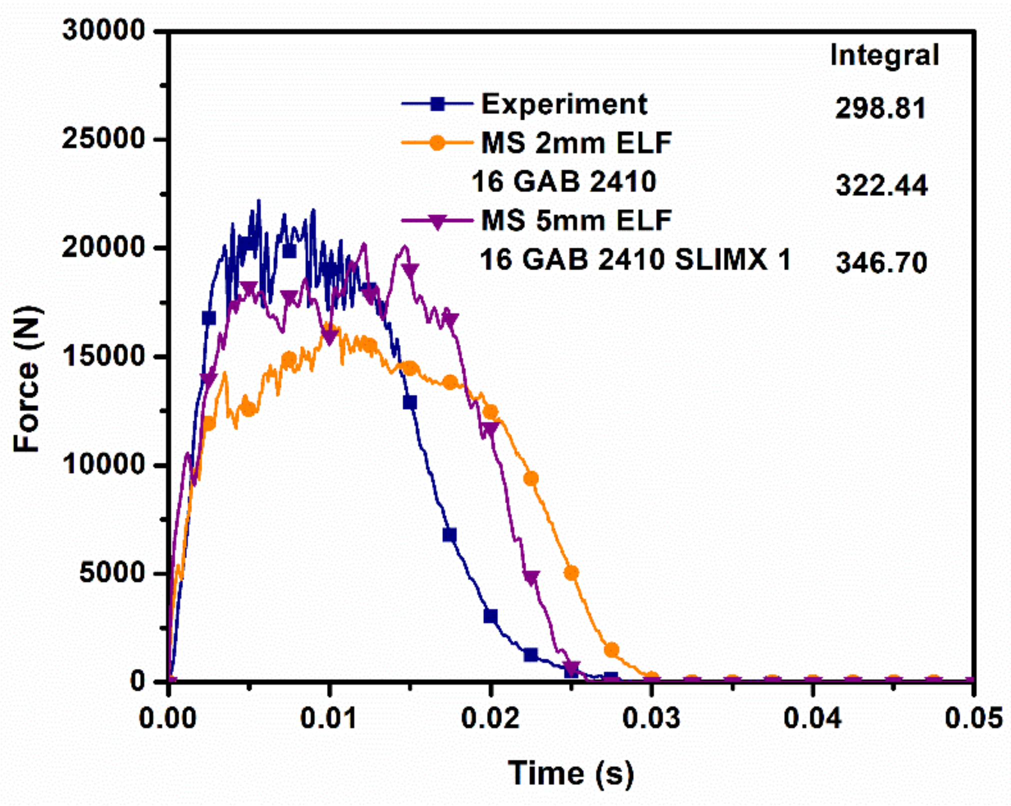
Impactor diameter: 2 in
Impactor weight: 80 kg
Initial velocity: 2.8 m/s
Energy: 300 J

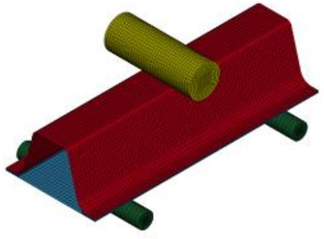






Max Hat deflection: 18.90 mm
Max Spine deflection: 6.36 mm
Peak Load: 22.20 kN





Sub component test 5 mm mesh size

Test was carried out in accordance with the simulated test conditions. 5 mm mesh size was used in full car simulations

Original MAT 54 Card

TITLE: Nylon V3 / currently used for full car simulations

1	MID	RO	EA	EB	(EC)	PRBA	(PRCA)	(PRCB)
	5000001	1.660e-09	9.340e+04	4833.0000	0.0	0.0163700	0.0	0.0
2	GAB	GBC	GCA	(KF)	AOPT	2WAY		
	750.00000	750.00000	750.00000	0.0	0.0	0.0		
3	XP	YP	ZP	A1	A2	A3	MANGLE	
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
4	V1	V2	V3	D1	D2	D3	DFAILM	DFAILS
	0.0	0.0	0.0	0.0	0.0	0.0	1000.00000	1000.00000
5	TFAIL	ALPH	SOFT	FBRT	YCFAC	DFAILT	DFAILC	EFS
	0.0	0.1000000	1.0000000	0.1000000	5.0000000	0.0186296	-6.1113491	0.6000000
6	XC	XT	YC	YT	SC	CRIT	BETA	
	570.79999	1450.0000	110.50000	30.900000	75.000000	54.0	0.5000000	
7	PEL	EPSF	EPSR	TSMD	SOFT2			
	100.000000	0.1000000	0.9000000	0.9000000	1.0000000			
8	SLIMT1	SLIMC1	SLIMT2	SLIMC2	SLIMS	NCYRED	SOFTG	
	0.0500000	0.6250000	0.1000000	0.6250000	1.0000000	10.0000000	1.0000000	
9	LCXC	LCXT	LCYC	LCYT	LCSC	DT		
	0	0	0	0	0	0.0		

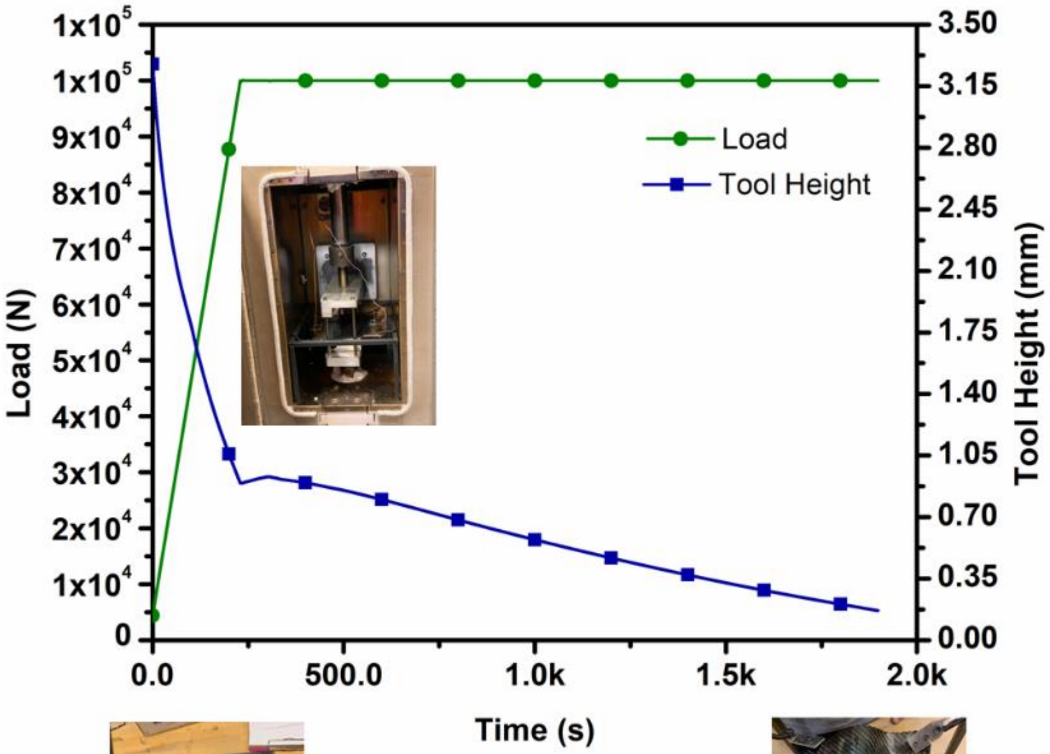
Modified MAT 54 Card

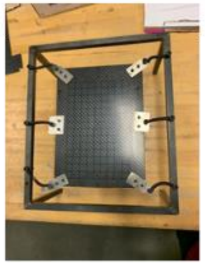
TITLE: TRIM 5m :: UD-AS4/NYLON-FVF=0.44 Compresion

1	MID	RO	EA	EB	(EC)	PRBA	(PRCA)	(PRCB)
	5000001	1.447e-09	1.004e+05	4833.0000	0.0	0.0163700	0.0	0.0
2	GAB	GBC	GCA	(KF)	AOPT	2WAY		
	2410.0000	2410.0000	2410.0000	0.0	0.0	0.0		
3	XP	YP	ZP	A1	A2	A3	MANGLE	
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
4	V1	V2	V3	D1	D2	D3	DFAILM	DFAILS
	0.0	0.0	0.0	0.0	0.0	0.0	1000.00000	1000.00000
5	TFAIL	ALPH	SOFT	FBRT	YCFAC	DFAILT	DFAILC	EFS
	0.0	0.1000000	1.0000000	0.1000000	5.1650000	1000.00000	-1000.00000	0.6000000
6	XC	XT	YC	YT	SC	CRIT	BETA	
	570.79999	1450.0000	110.50000	30.900000	75.000000	54.0	0.5000000	
7	PEL	EPSF	EPSR	TSMD	SOFT2			
	100.000000	0.0500000	0.9500000	0.9500000	1.0000000			
8	SLIMT1	SLIMC1	SLIMT2	SLIMC2	SLIMS	NCYRED	SOFTG	
	0.0500000	0.6250000	0.1000000	0.6250000	1.0000000	10.0000000	1.0000000	
9	LCXC	LCXT	LCYC	LCYT	LCSC	DT		
	0	0	0	0	0	0.0		

Material model slightly underpredicts overall stiffness response but accurately predicts overall failure

Progress: Manufacturing & Simulations

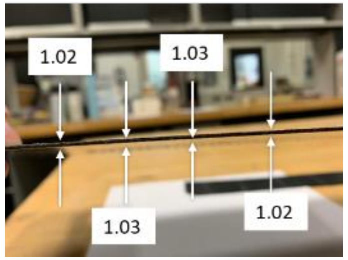




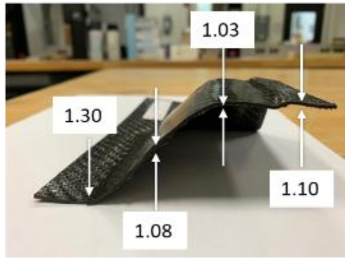
Pre-consolidated Blank

Formed Part

Before Forming

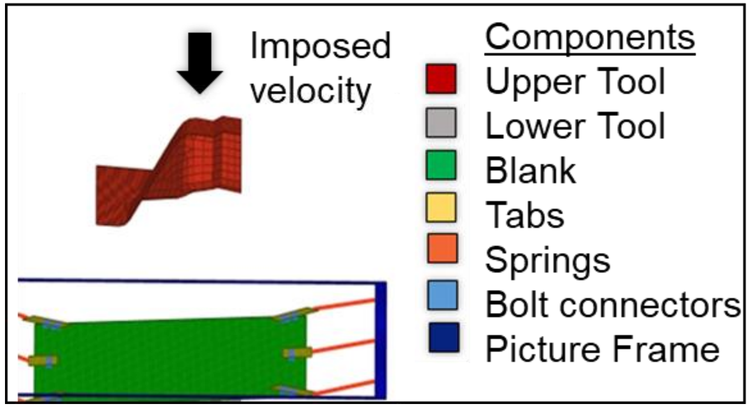


After Forming

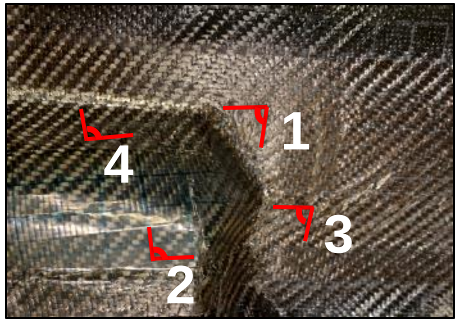


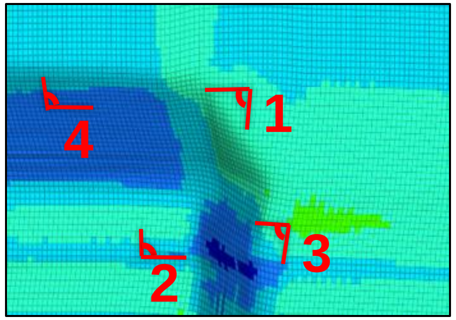
Variables

1) Material supplier
2) Process paraments and
3) Tool orientation
4) Silicon Bladder



Simulation Setup





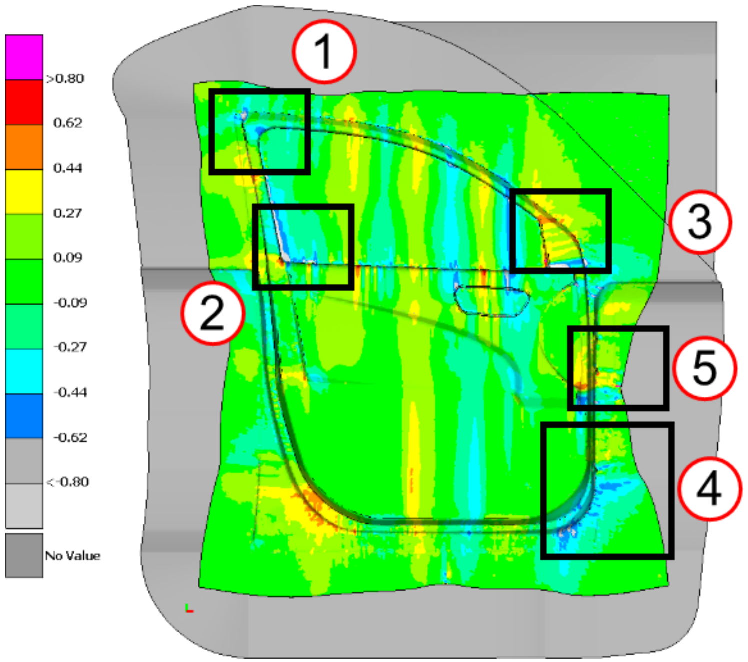
Experiment vs Simulation: comparison of Shear angle

Shear angle (°)	Test	Simulation
Location 1	81.027	82.482
Location 2	88.927	88.360
Location 3	75.707	76.95
Location 4	98.909	100.01

Trials show satisfactory subcomponent forming without use of silicon bladder thus reducing manufacturing complexities
Simulation comparison with trials confirms accuracy of shear angle prediction upto 98%

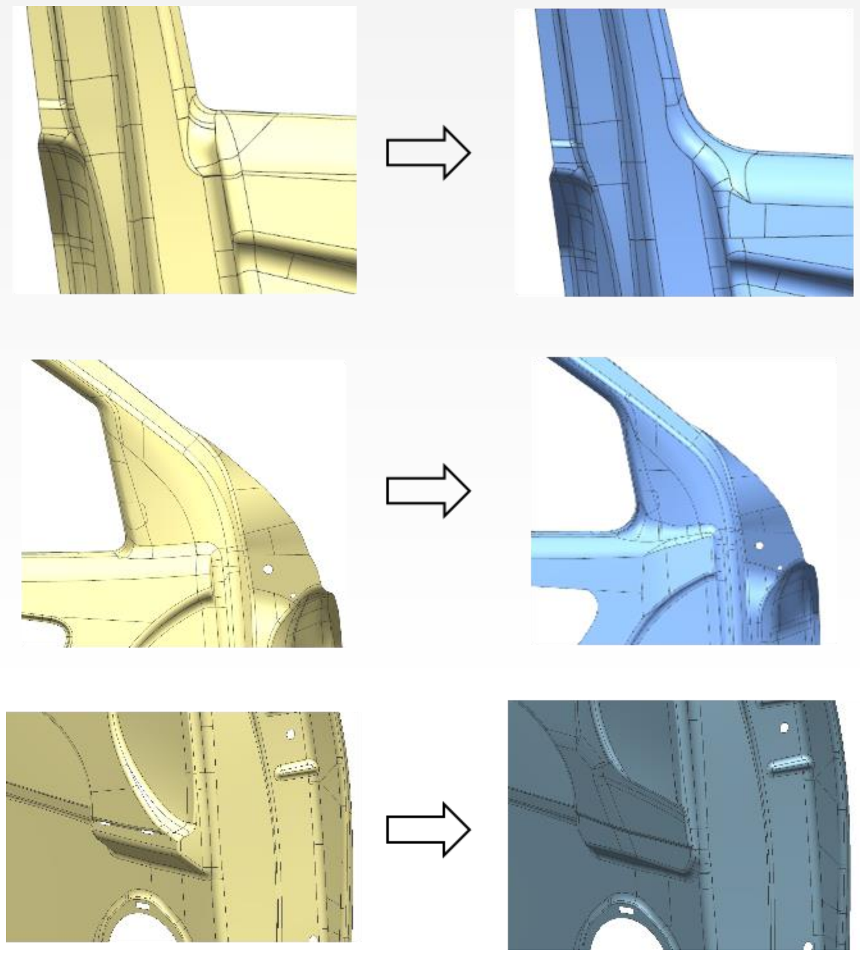
Progress: Manufacturing Simulations

Forming Simulations (Before)

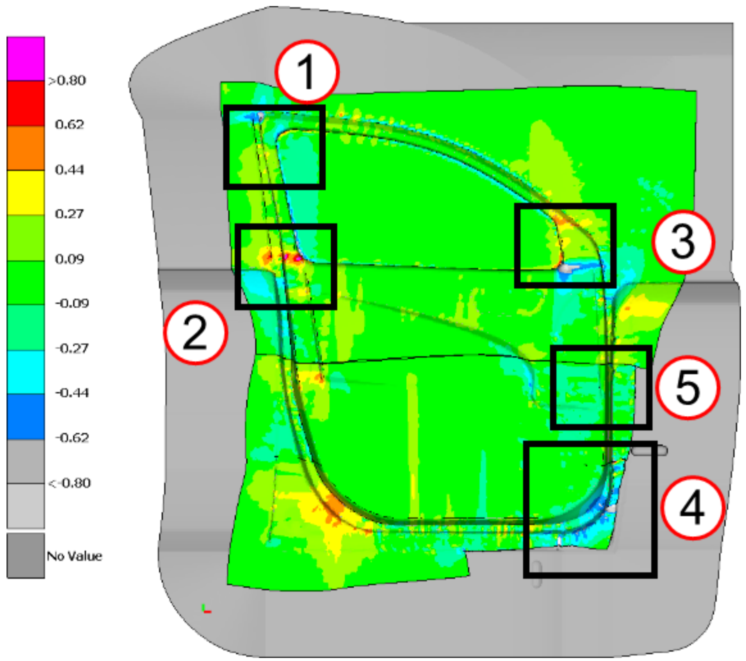


Five highlighted regions were critical as they showed highest shear angle.

CAD Changes



Forming Simulation (After)



The CAD changes, material handling and strategic use of pre runners was crucial in reducing high shear angles in the highlighted sections.

Shape changed by increasing radius and decreasing forming depth to prevent tear based on forming simulation. Location of pre-runners and ply stack up optimized.

Progress: Final Design

Structural Components

Inner frame

Thermoformed inner panel + integrated trim.

- **Material: PA 6 + 50 wt % Woven CF**

- **Anti-intrusion beam**
- **Hot stamped and welded**
- **Material: Ultra high strength steel**

Inner beltline stiffener

- **Thermoformed shell with mounting interfaces for the inner components.**
- **Material: PA 6 + 50 wt % Woven CF**

Outer beltline stiffener

- **Extruded aluminum beams with stamped handle mount.**
- **Material: Aluminum 6061**

Lower Reinforcement

- **Stamping**
- **Material: Aluminum 6061**

Aesthetic Components

To minimize weight and cost, our door has no interior panel. Instead it has a few injection molded / 3D printed parts to meet functional requirements

Baseline Trim Weight: 3.49 kg
Snap fit Trim weight: 1.34 kg

Innovative Design (Parts consolidation + No Trim) and Multi material Strategy (Strategic use of Steel and Aluminum)

Progress: Weight Targets

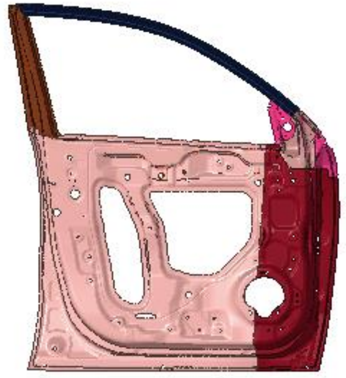
Production Version

- Complexity of the UD + Woven material system necessitates equipment like automated tape placement and material handling system.
- Dramatically increases tooling complexity and cost.

Prototype Version

- Simpler, relatively easier to handle and form.

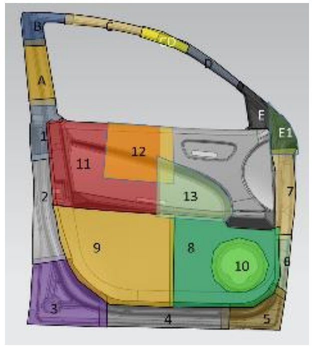
Baseline High Strength Steel



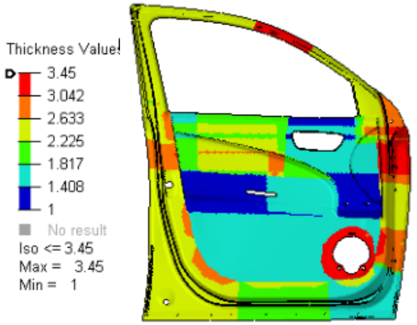
Production Version Thermoplastic Composites

- Ply Layup: 1 mm Woven Base + UD Patches
- Minimum manufacturing thickness : 0.15 mm
- Available ply orientations: [0 90 +45 -45]

Ply layup



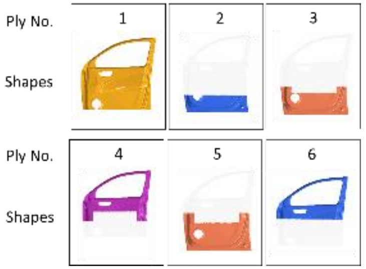
Thickness distribution



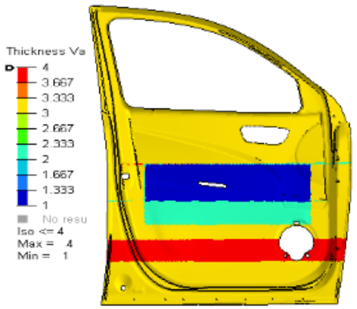
Prototype Version Thermoplastic Composites

- Ply Layup: 6 layers of optimized Woven ply
- Minimum manufacturing thickness – 1mm
- Available ply orientations: [0 90]

Ply layup



Thickness distribution



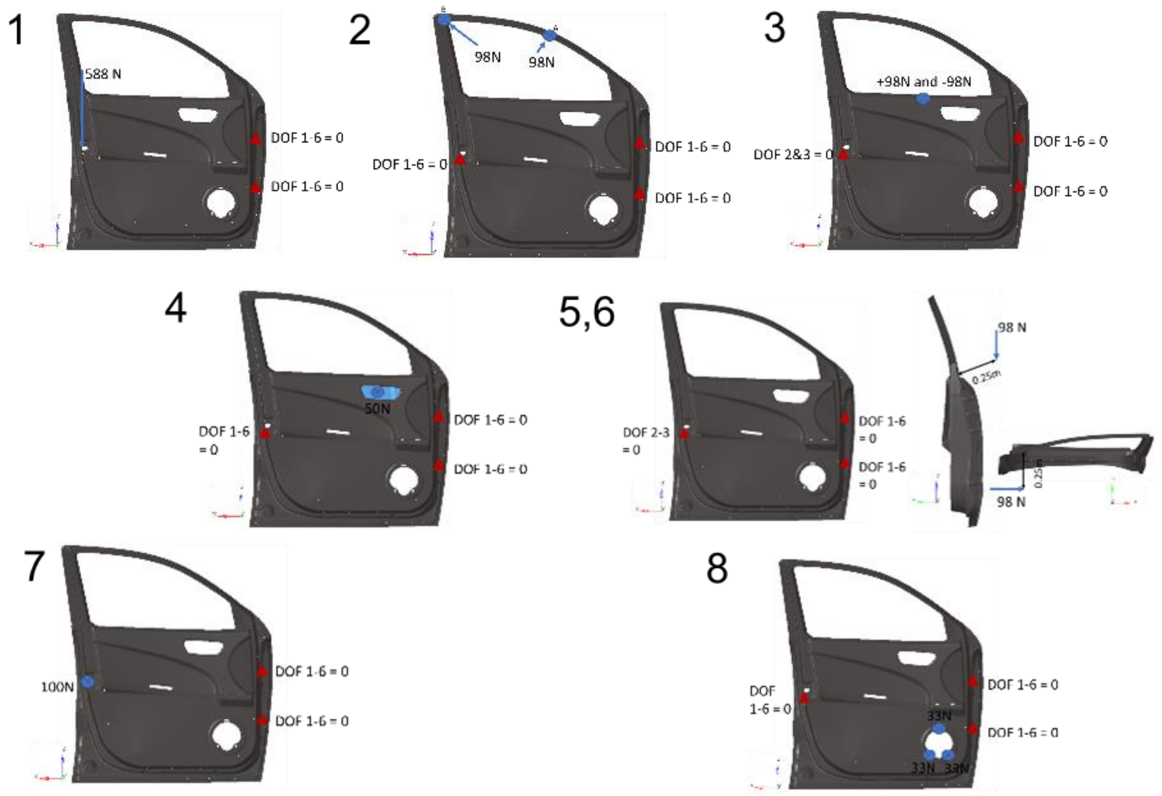
Material Inner Frame	High strength steel	Carbon/PA6 composite (Woven + UD tapes)	Carbon/PA6 composite (Woven layup)
Door Structural Weight	15.44 kg	8.44 kg	10.1 kg
Interior Trim	3.5 kg	1.32 kg	1.32 kg
Glass Assembly	3.7 kg	2.59 kg	2.59 kg
Carryover Parts	7.35 kg	7.35 kg	7.35 kg
Total Weight Reduction %	NA	- 36.66%	- 31.32%

~37% weight savings achieved for production version of composite door.
Carryover parts comprise of 24% of door weight this presents a huge potential for suppliers

Progress: Structural Performance

Static load cases

- The linear static load cases represent door performance for daily use and occasional misuse of the door
- The composite design optimization is carried out for the listed static load cases.
- All static load cases are well satisfied for the composite door.



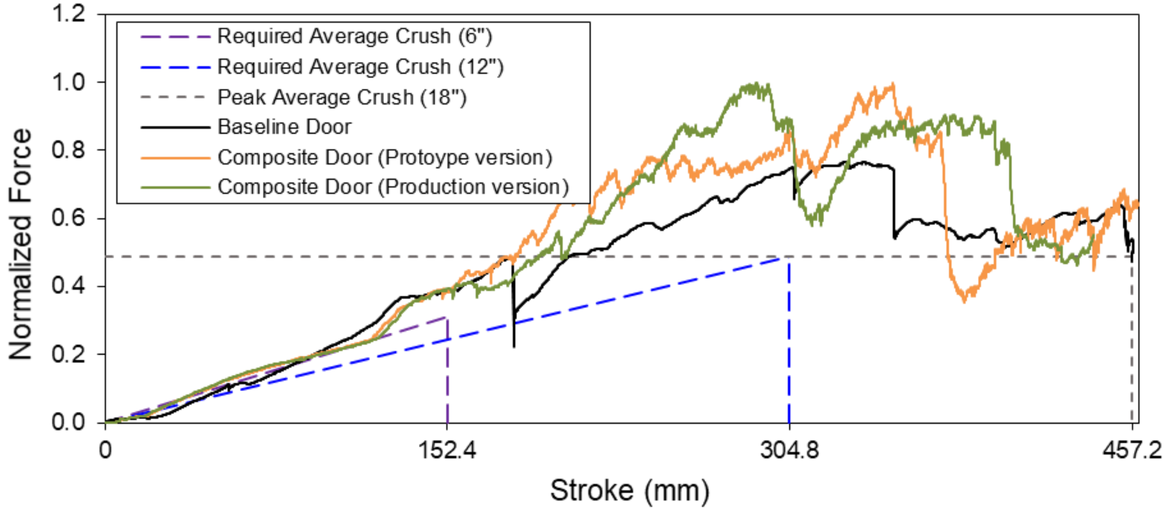
S No	Load Cases	Target	Composite door response (% Improved from baseline)	
			Production version	Prototype version
1	Door Sag - Fully open	< Baseline	53%	50%
2A	Sash Rigidity at point A		17%	9%
2B	Sash Rigidity at point B		46%	55%
3	Beltline stiffness-Inner panel		52%	79%
4	Window regulator (Normal)		73%	73%
5	Mirror Mount rigidity in X		10%	2%
6	Mirror Mount rigidity in Y		77%	66%
7	Door Over opening		5%	11%
8	Speaker mount stiffness		3%	43%

Both Production and Prototype versions of the composite door satisfy all static load cases with more stringent target definitions set by the OEM partner.

Progress: Structural Performance

FMVSS 214 S Quasi-static Pole test

- A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.



FMVSS214 S OEM Requirements	Composite door response (% Improved)	
	Production version	Prototype version
Initial average crush (6'')	+18%	+15%
Intermediate average crush (12'')	+86%	+75%
Peak average crush (18'')	+121%	+115%

IIHS Side Impact moving deformable barrier test

- A moving deformable barrier of mass 1500 kg is impacted with a stationary vehicle at 50 km/h.
- A 5th percentile female SID IIs dummy is included in the test as per NCAP guidelines.
- A gauging metrics for IIHS SI- MDB is defined
  - Success (Green) – If intrusion is below baseline target values (<b)
  - Tolerable (Yellow) - If intrusion is more than baseline values but smaller than 10 % difference (>b, <b+10%)
  - Failure (Red) – If intrusion is 10% above baseline value (>b+10%)
- No exposed crack in the door interior.

Key Performance Indicator	Composite door response (% Improvement)	
	Production	Prototype
Safety survival space	5.6%	Results delayed as OEM is closed due to COVID-19 and their servers were inaccessible
Maximum roof intrusion	8.0%	
Maximum window sill intrusion	12.7%	
Front door dummy hip intrusion	21.4%	
Max door lower intrusion	0.5%	

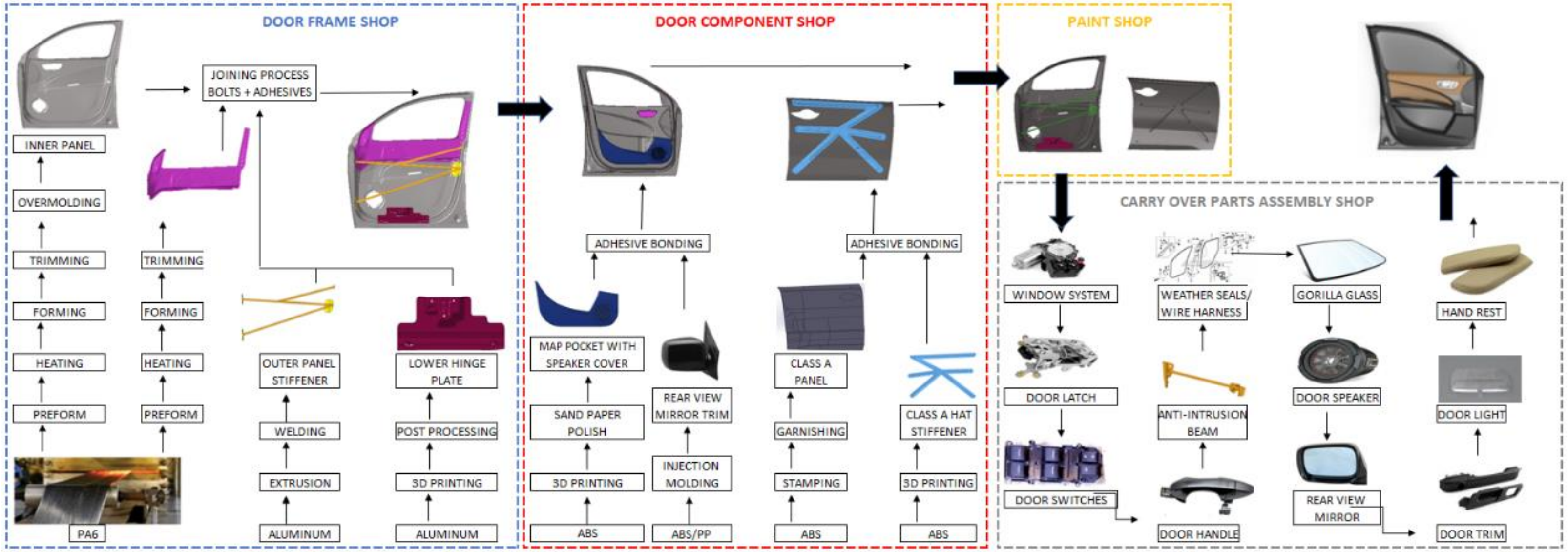
The average crush resistance for both versions of composite door is significantly higher than the FMVSS214 requirements. The production version of composite door outperforms baseline door for IIHS MDB test.

Progress: Cost Modelling

Parametric cost model assumptions:

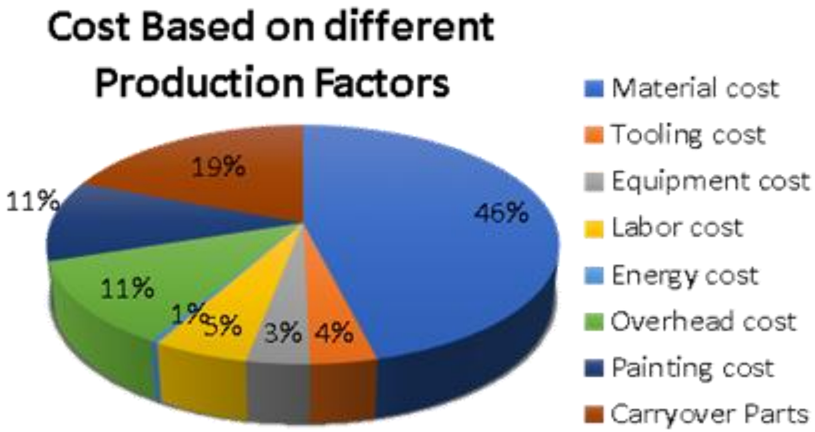
- Production volume per year is assumed to be around 20,000
- Total number of direct and indirect workers for each machine are assumed to be 4
- Rate of overhead (18~24% of total cost) is assumed by experience | Cost of carry over parts (~$180) is assumed to be constant
- Cost of raw martials for carbon fiber nylon composites range from $31 to $46 (depending on reinforcement type)
- Cost of carbon fiber assumed is > $ 7/lb

Process Map



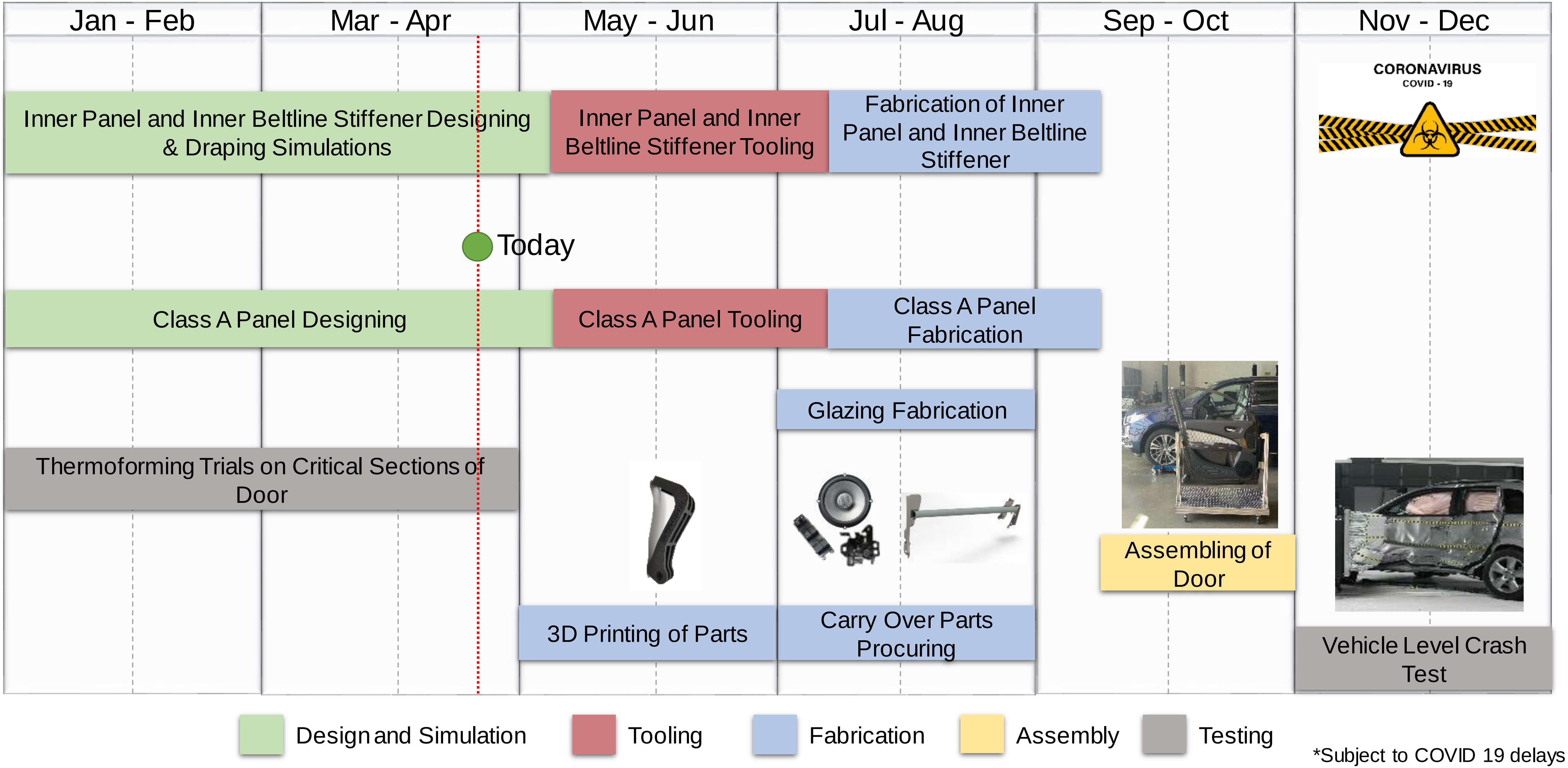
Cost/Pound saved by door subsystem

Parts	Baseline Weight (kg)	Lightweight weight (kg)	% Mass Reduction	$$/Pound saved
Structural parts	15.44	8.44	45%	4.02
Non-structural parts	9.37	4.97	47%	4.18
Carry Over Parts / Painting	6.29	6.29	0%	0
Total	**31.1**	**19.7**	**36.66%**	**5.40**



A total cost increase of $ 5.40/lb saved was achieved
(**DOE target $ 5 /lb saved**) for the ultralightweight composite door.

Progress: Manufacturing



*Subject to COVID 19 delays

Response to Reviewer Comments

Comment from 2019 Annual Merit Review	Response
This reviewer noted that the project accomplished the weight and performance targets. There were some areas where there needed to be changes. This reviewer is not sure why the need to add aluminum (Al) at the bottom of the door versus making a change in the composite in that area of the door and compare the results. If a composite patch area could have been made it would have eliminated a stamped Al part with bonding to the door.	The team initially considered the door design with all composite parts. However it was realized that in order to achieve high crush resistance requirements provided by the OEM partner especially for the FMVSS 214S load case where a rigid pole is used to deform the door for a large deformation of 18 inches , placing a thin metal patch near the point of impact would be a more feasible option since a thin composite patch regardless of having high strength and stiffness cannot sustain for such a large plastic deformation.
It does seem that the tooling fabrication and manufacturing element of this project is coming pretty late in the program timeline and compresses critical elements of hardware development, fabrication, assembly, and testing. Given the delays related to installation of facilities not yet in place at the onset of the effort, this is not necessarily unexpected. This reviewer is concerned, however, that lead times in tooling and some necessary learning curve elements in molding the inner and outer panels will challenge even this extended schedule. The work is worth doing, so no additional cost extensions or other means to accommodate an extended schedule should be tolerated.	The team understands the concerns of the reviewer. The reason the tooling element arrived late was due to a couple of reasons ranging from most aggressive lightweighting target of all three teams, delay in receiving baseline CAD, relatively new material systems, OEM target > FMVSS 214s targets. The team is performing thermoforming on critical elements of the door in order to gain understanding and learning for inner panel. The team has also decided on a relatively simpler prototyping version given the geometric complexity of the baseline door. Additionally the team has identified and engaged partners like Proper Tooling and Lanxess that have ears of technical experience and know-how for this process.

Response to Reviewer Comments

Comment from 2019 Annual Merit Review
The reviewer commented that progress and accomplishments are good for FY 2018. The concept of the door design has progressed. This reviewer had wanted to see a full Bill-of-Materials with weights and costs. This reviewer questioned the use of thinner material with selected ribbed reinforcements on the exterior panel. This often generates unacceptable witness marks or “read through” on the class-A surface. The design does not include any water barrier to keep the window motor, speaker, and other internal components dry during vehicle use. The exploded views should show the full door construction and all the components. The assembly and painting of the door has not been addressed in this project, which often influences the design, especially for composites. The claimed crash accomplishments are difficult to verify because there are as yet no physical tests to CAE comparisons shown in the review. The CAE guidance without any physical testing is suspect. A static stiffness test and a simple natural modes test to CAE would be valuable comparisons.

Response
Class A surface: The team has not reduced the thickness of the class A panel, it has increased the thickness by 60%. Witness marks will not appear on the panel because the class A panel and its stiffener sections are manufactured using two different processes (Thermoforming and 3D printing) and finally they will be attached to each other. **Water Barrier:** The current door is designed as a wetbox very similar to the baseline door. The components within are carryover in nature are to the best of our knowledge rated to work in high moisture environment **Exploded view having full door assembly:** Technical backup slide 4 **Assembly and painting:** Slide 13 **Claimed crash accomplishments:** Subcomponent(s) tests under dynamic environment were performed, material model used was calibrated and verified (Slide 7).

Collaborations

Key Organizations	Role	Responsibilities
Clemson University	Principal investigator	• Project management • Design development • Linear & NVH analysis • Cost & factory modeling • Discontinuous fiber material characterization
University of Delaware	Co - PI	• Non-Linear analysis • Continuous fiber (UD and Woven) material characterization • Design support
Honda The Power of Dreams	OEM Partner	• Target definitions • Student mentoring • Computation support for running complex simulations • Component & vehicle crash testing
LANXESS Energizing Chemistry	Supplier	• Material Supplier • Manufacturing Simulation Support
Proper Group International Advanced Engineering • Superior Technology	Supplier	• Manufacturing/tooling design & simulation • Prototyping

Suppliers, software and general participants

BASF We create chemistry · Barrday · Altair · LSTC Livermore Software Technology Corp. · MSC Software · Moldex3D Molding Innovation · SIEMENS

Remaining Challenges & Barriers

1. COVID 19

1) Talks with our tooling partners began August 2019.

2) CAD has been analyzed; quote formalized as per inputs from manufacturing simulations.

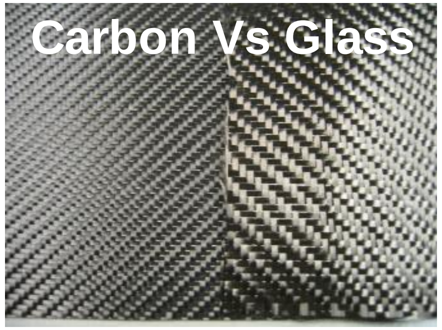
3) Currently tooling has been delayed as tooling for ventilator parts has higher priority.

2. Manufacturing

1) The team understands the challenges and barriers involved in manufacturing and assembly and is working tirelessly to chart and overcome these.

2) The team hopes to leverage experience gained from the manufacture & assembly of our previous low-cost prototype door.

3. Cost



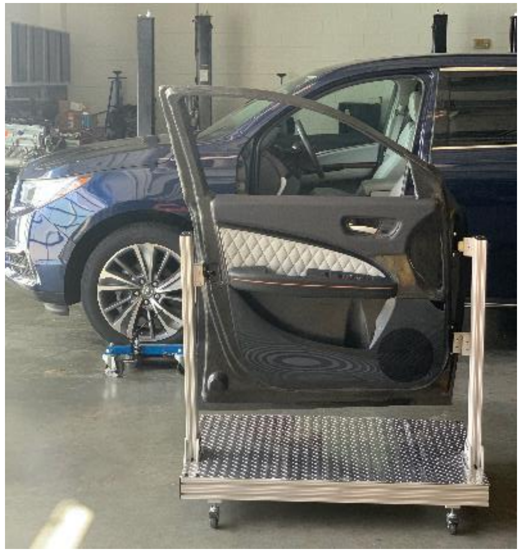
1) The high cost of carbon fiber remains a barrier for cost targets.

2) Glass fiber woven composite door met most static targets.

	CF	GF
Lightweighting	37 %	>25%
Material cost	X	1/10 x
Overall door cost	$ 936	$ 805
$/lb saved	$ 5.4	$ 0.21

Proposed Future Work

Tooling + Manufacturing



- Tooling: Our priority is to go into tooling as soon as possible having finalized CAD.
- Our tooling partner (Proper) and material supplier (Lanxess) have technical experience in designing dies suited for forming thermoplastic composite sheets.

Testing

Requirements	Description	Standard	Location
Fit and Finish	Finish	SAE J361	CUICAR
	Fit	SAE J361	
Side Impact	FMVSS 214 (deformable barrier)	FMVSS 214	Honda
	FMVSS 214 (quasi-static pole)	FMVSS 214	
Static stiffness test	Strong open and close	Honda specific	CUICAR
	Door Sag (open)		
	Door sag (closed)		
	Frame stiffness		
	Belt Line stiffness		

- Team is currently working with OEM our partner to finalize SOP, logistics and timeline for these tests.

*Any proposed future work is subject to change based on funding levels

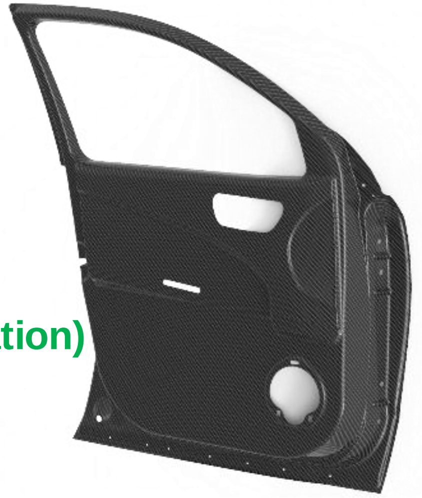
Summary

Baseline Door

Structural Parts	17 Parts
Structural Mass	15.44 kg
Total Parts	61
Total Mass	31.1 kg
Trim + Glazing	3.7 kg + 3.49 kg
Performance	5 star
Costs ($/lbs saved)	NA

Ultralightweight Composite Door

Structural Parts	8 Parts
Structural Mass	8.4 kg
Total Parts	52
Total Mass	19.7 kg
Trim + Glazing	2.59 kg + 1.34 kg
Performance	Meets or exceeds (Simulation)
Costs ($/lbs saved)	$ 5.4 ($ 5 permitted)

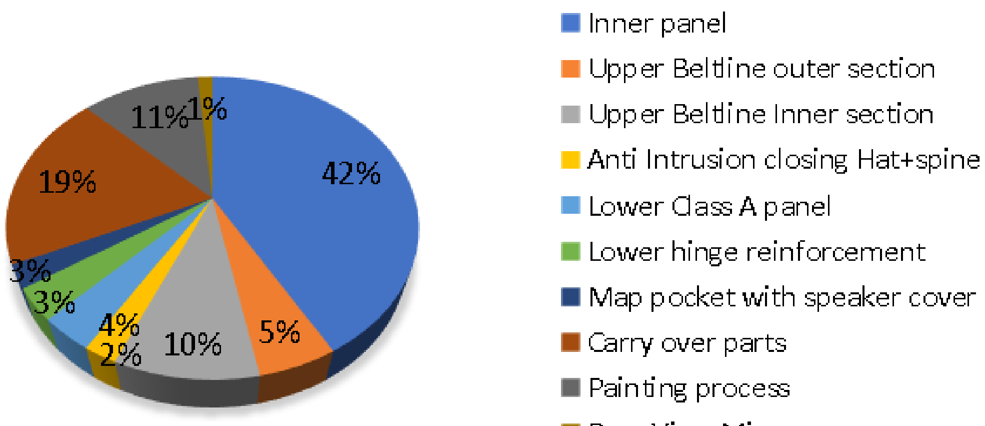


- Subcomponent testing, re-calibration of MAT 54 material card and validation.
- Thermoforming trials on critical door features and establishing manufacturing to response pathway.
- CAD Design released for tooling after incorporating manufacturing simulation inputs.
- Parametric cost model was presented.
- Manufacturing and testing timeline presented

Technical Back Up Slides

Technical Backup Slide 1: Cost Model

Cost Based on door subsystems



Cost breakdown by door subsystems

Sr. No.	Part	Cost
1	Inner panel	390.67
2	Upper Beltline outer section	48.65
3	Upper Beltline Inner section	88.67
4	Anti-Intrusion closing Hat+spine	20.76
5	Lower Class A panel	33.92
6	Lower hinge reinforcement	31.60
7	Map pocket with speaker cover	22.79
8	Carry over parts	181.00
9	Painting process	104.27
10	Rear View Mirror	12.93
	Total Cost of door	**935.26**

Cost breakdown by various production factors

Sr No	Cost factors	Cost
1	Material cost	437.17
2	Tooling cost	33.56
3	Equipment cost	31.86
4	Labor cost	48.22
5	Energy cost	4.14
6	Overhead cost	108.23
7	Painting cost	104.27
8	Carryover Parts	181.00

Weight **31.8 kg**
Frame weight **15.1 kg**
Overall parts **61 parts**
Accessible Area **0.14 m^2**

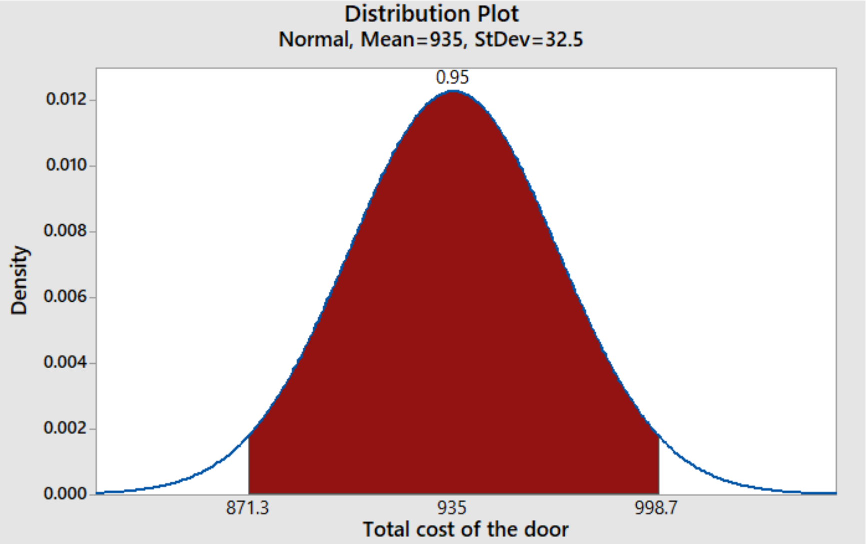
Weight **19.7 kg**
Frame weight **8.4 kg**
Overall parts **52 parts**
Accessible Area **0.56 m^2**
No. Composite Parts **2**

Technical Backup Slide 2: Cost Model

- A parametric cost model is setup which shows the influence of identified parameters on final cost of the ultralightweight door.
- A normal distribution curve with 95% confidence interval is obtained which incorporates all the identified parameters. The cost varies between $871-$998.

Identified parameters	Identified Variations	Total Cost ($)
Electricity cost per kWh(cents)	7.5~17	871 ~998
Scrap rate(%)	4~15	
Mold life(years)	6~11	
Equipment life(years)	5~13	
labor wage($)	15~28	
Material cost per kg (S)	36~46	

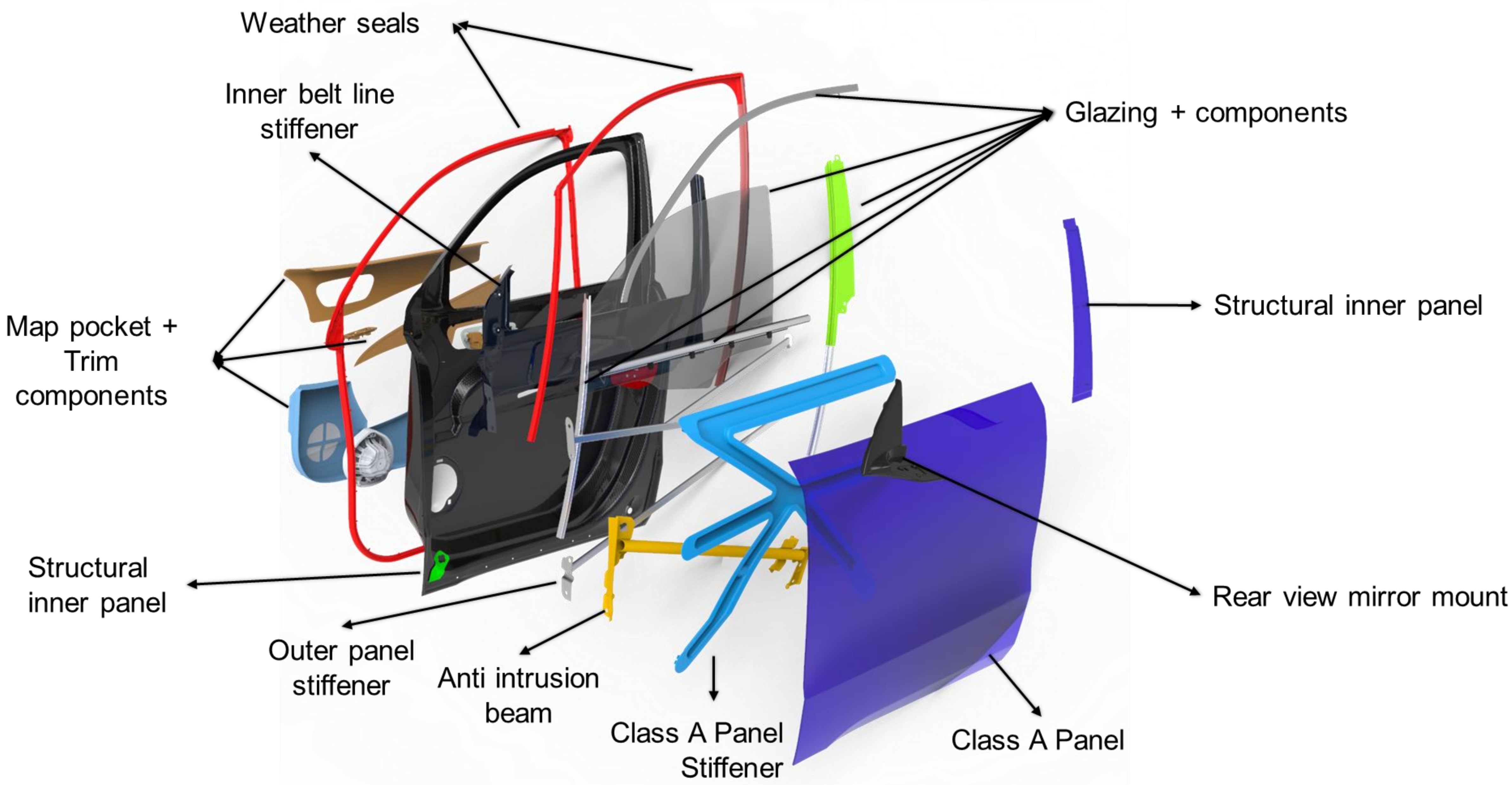
S.no	Parameter	Raw data distribution	Mean ± 2SD	Total cost distribution	Total cost (USD)	Probability
1	Electricity rate (cents/kWh)	Log logistic	7.5~15	Lognormal	933~937	0.94
2	Scrap rate (%)	Lognormal	4~13	Largest extreme value	907~960	0.95
3	Mold life (years)	Log logistic	3.5~12.5	Logistic	920~972	0.96
4	Equipment life (years)	Lognormal	5~13	Normal	931~939	0.94
5	Labor wage ($/hr)	Weibull	15~25	Weibull	929~950	0.95
6	Overhead rate (%)	Normal	15~27	Normal	904~981	0.95
7	Material cost ($)	Weibull	64~85	Log logistic	876~991	0.95



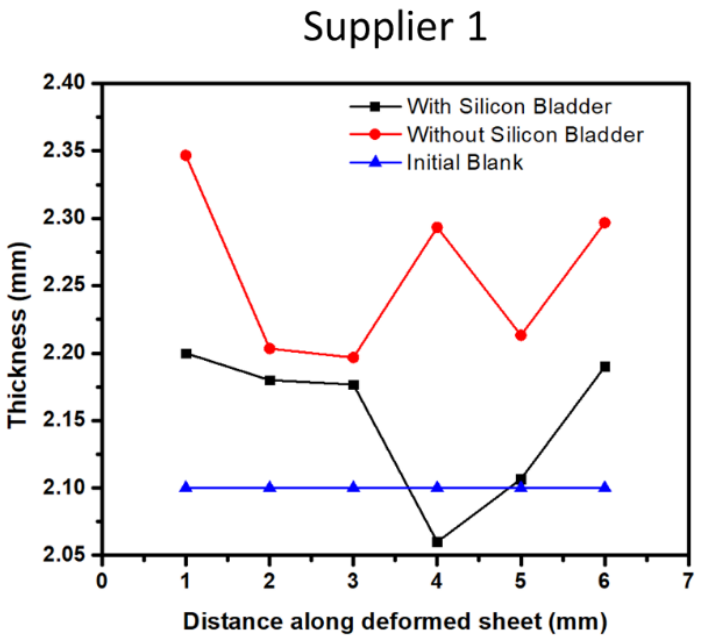
Technical Backup Slide 3: Glass fiber door

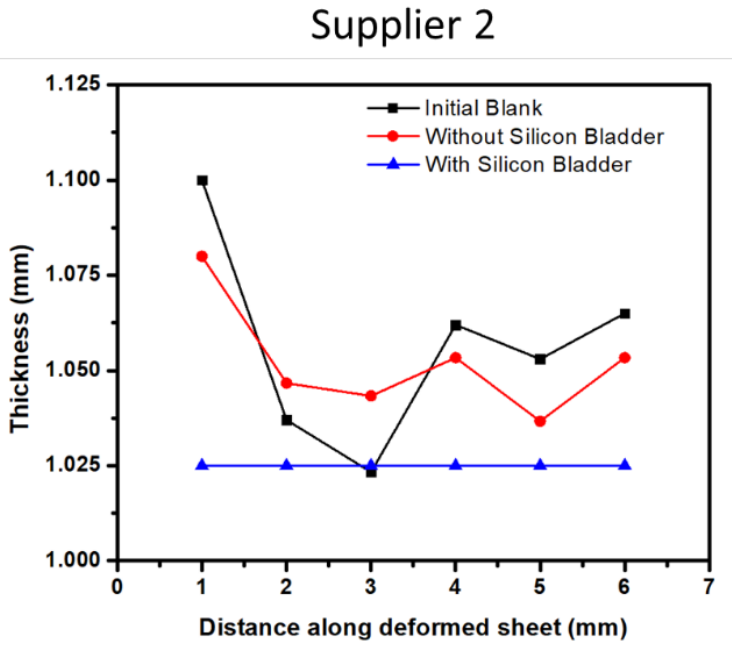
S.no	Target category Subcase	Target values (units)	Carbon Composite (% Improvement)	Glass/PA6 Composite (% Improvement)	Glass/PP Composite (% Improvement)
1	Mass Target				
1.1	Structural frame mass	< 7.42 kg	10.15 (-31.16%)	11.5 (-26.82%)	11 (-28.42%)
2	Frame Related				
2.1	Door Sag - Fully open	< Baseline (mm)	50%	15%	26.4%
2.2	Sash Rigidity at point A		9%	-109%	-70%
2.3	Sash Rigidity at point B		55%	-7.5%	7.5%
2.4	Beltline stiffness-Inner panel		79%	53%	60.7%
2.5	Window regulator (Normal)		73%	16.4%	26%
2.6	Mirror Mount rigidity in X		2%	-218%	-155.4%
2.7	Mirror Mount rigidity in Y		66%	19.5%	35.5%
2.8	Door Over opening		11%	-76.1%	-51%
2.9	Speaker mount stiffness		43%	-34.3%	-34.1%
2.10	Outer panel stiffness		80%	80%	80%

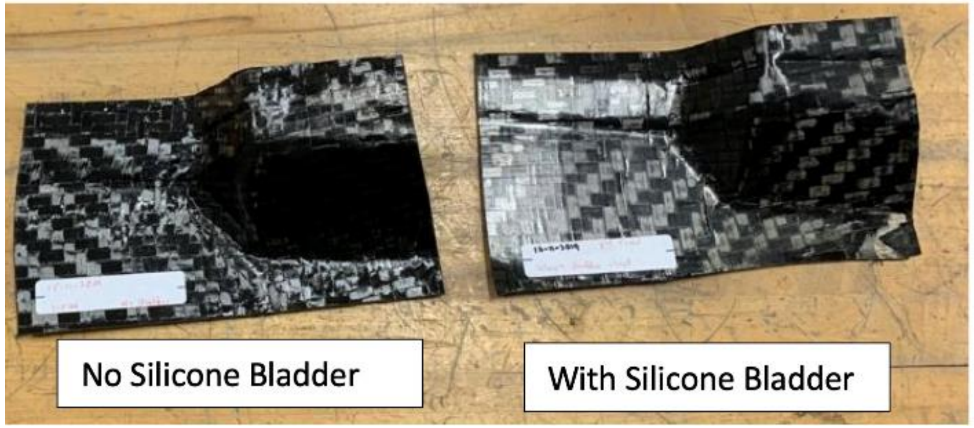
Technical Backup Slide 4: Exploded View

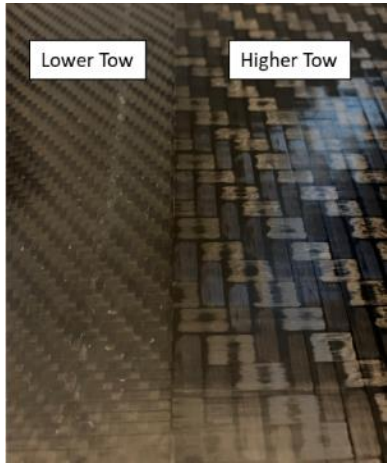


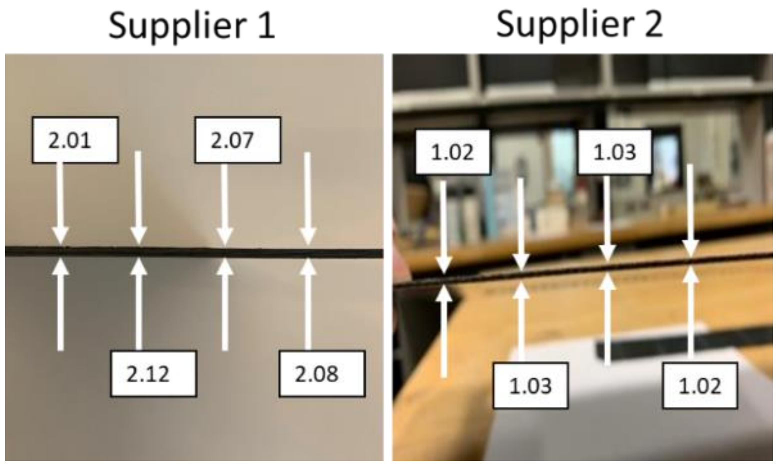
Technical Backup Slide 5: Thermoforming











Sample	Silicon Bladder (Y/N)	Comments
Supplier 1	N	Fibers were not oriented properly, and the upper face was not flattened
Supplier 1	Y	Proper finish on the side of the bladder and flattened surface
Supplier 2	N	Both gave the same results, flattened surfaces, and proper finish
Supplier 2	Y	